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1.—Amphibolites and Associated Pre-Cambrian Rocks of part of the Phillips River Goldfield, Western Australia*

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The Cocanarup area in the Phillips River Goldfield is composed of a sequence of meta-volcanic rocks which form a belt 1 to 1½ miles broad, trending NE. to SW., flanked on the north-west by a narrow band of schists which pass, through migmatites, into granodioritic gneiss. To the south-east, a magmatic granodiorite intrudes the meta-volcanics. The meta-volcanic rocks are predominantly fine-grained amphibolitic lavas and agglomerates although some non-amphibolitic volcanics do occur and a coarse amphibolitic hypabyssal phase of the lavas does form small intercalations. The term "Phillips River Meta-volcanics" has been suggested for these lavas, agglomerates and genetically related hypabyssals.

Within the schists, zones of crushed and laminated rocks indicate localized attenuation and shear. The gneiss is a product of granitization of a folded meta-sedimentary sequence, the folding of these rocks, the schists and the Phillips River Meta-volcanics being about fold axes which plunge in the direction 110° to 130°. The granodiorite and meta-volcanics are intruded by a suite of basic dykes which are now amphibolitic. Occasional dacitic dykes also cut these rocks as well as the amphibolitic dykes. Flat-lying pegmatite sheets have a prominent development within the belt of meta-volcanics. All the rocks of the area, with the exception of recent superficial sediments, are cut by ENE.-trending quartz dolerite dykes which have dioritic or gabbroidal cores.

The gneiss and its marginal migmatites and schists are probably a petrologically distinct province from the Phillips River Meta-volcanics and granodiorite, their present adjacent position being due to later faulting.

Introduction

The rocks described in this paper are from an area centred about Cocanarup homestead, which is situated at the crossing of the Phillips River and the Ongerup-Ravensthorpe road, nine miles south-west of Ravensthorpe townsite in the Phillips River Goldfield. The purpose of the investigation was to study the field relations and petrology of the rocks, especially in the belt of amphibolites. In part this detailed study was undertaken in an effort to elucidate the geological map of the Ravensthorpe-Kundip area which lies to the east (Woodward *et al.*, 1909), and by examining and correlating the rock types with the aid of thin section microscope studies to assist future geological mapping in the area.

Unfortunately the area chosen presented many fundamental difficulties, foremost of which was the lack of a reliable topographical survey map. Moreover, air photographs were not available. The only geological information concerning the surrounding country was that contained in the early Geological Survey reports of 1900-1914. They related to the gold and copper mineralized areas of Ravensthorpe and Kundip. Of these reports only Bulletin 35 (Woodward *et al.*, 1909) contains any significant geological information, but it was found that the petrology in this Bulletin was of little use and structural information was almost entirely lacking.

The relation of the greenstones of the Phillips River Goldfield to the similar mineralized greenstone areas of the Yilgarn (Southern Cross) and Kalgoorlie—Norseman Goldfields is shown in Fig. 1. It is unlikely that there is any close connection in time between these three occurrences of similar rocks, but nevertheless it will be of interest to be able to compare the features of development with those of the better known mining districts.

The mapping was carried out mainly single-handed by a pace and compass survey based on a broad chain and compass net. For example, the road, the Phillips River south of the road, and the upper reaches of the Twertatup Creek were plotted by chain and compass, while the

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topographic and geologic features on either side were plotted by pace and compass traversing. The greater part of the geological information was obtained from observations in the stream channels, as soil obscured most of the country between the streams.

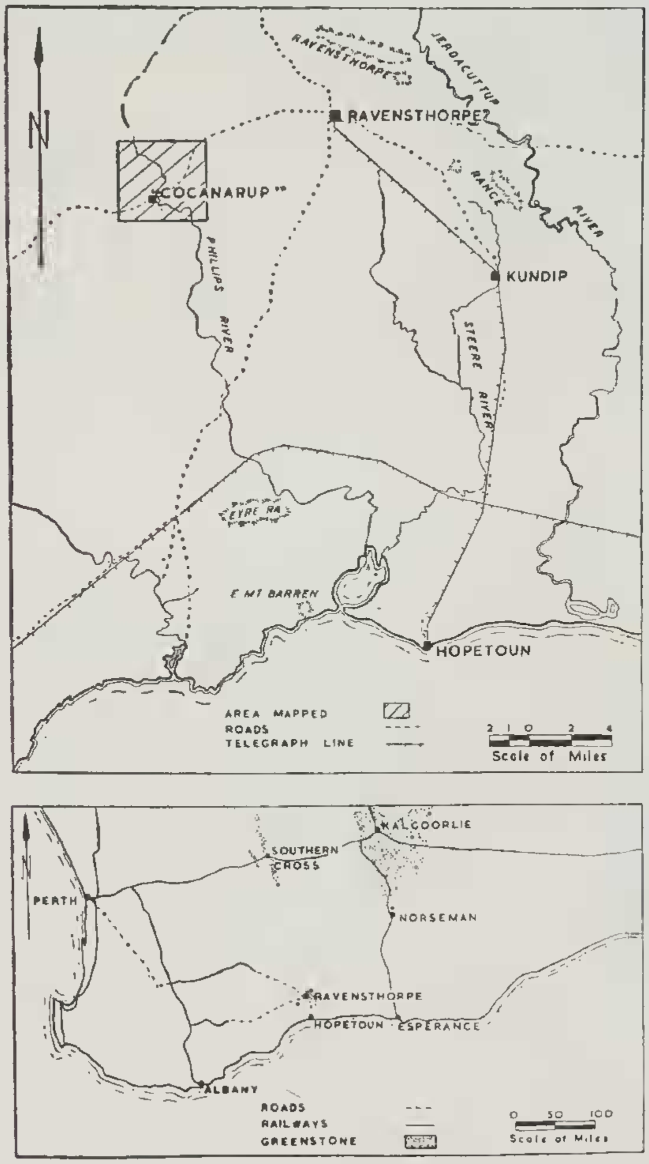


FIG. 1.—Locality Maps.

In the valley of the Phillips River where it cuts the type section of the Phillips River Meta-volcanics, the problem of mapping at least four ages of dark basic rocks, often complexly inter-related, is further hampered by the presence of a black manganese stain on the exposed rock surfaces. The inter-relationships of all the rocks, including light pegmatitic and meta-sedimentary bands are obscured by this manganiferous paint.

Of five hundred rock specimens collected and macroscopically examined, two hundred and sixty were sliced and examined microscopically in an effort to become familiar with the main rock types. The detailed petrography of the rocks is available in manuscript form in the Department of Geology of the University of Western Australia.

With regard to nomenclature, the term "greenstone" which has had such a wide usage in the geological literature of the goldfields of Western Australia, has not been favoured in this paper. Wherever it has been used it is in a very generalized sense, e.g., "the greenstone areas of the Yilgarn, &c." implies an area consisting predominantly of meta-basic volcanics and hypabyssals. It is a useful field name but too vague and non-descriptive in its meaning to be a satisfactory term in a detailed investigation.

In preference to "greenstone" the term "amphibolite" is used. This is defined as a metamorphic rock consisting dominantly of hornblende and plagioclase. It does not include the hornblendic rocks which are the product of late-magmatic deuteric alteration, such as the quartz diorite of this area. It can be subdivided into "meta-igneous amphibolite" and "meta-sedimentary amphibolite". It is a precise term in that it implies the metamorphic nature of the rock and its main mineralogic feature.

Epidiorite is another common term in the literature on metamorphosed basic igneous rocks. It implies a meta-igneous amphibolite, as defined above, and thus does not include deuterically derived hornblende-rich rocks. In order that the nomenclature might remain as simple as possible the name "epidiorite" is not used in this paper.

All the igneous rocks have been referred to the classification of igneous rocks by Hatch *et al.* (1949). Thus the "soda granite" mentioned in the earlier petrological work on the Phillips River rocks is referred to here as "granodiorite". The name "porphyry", so commonly used for acidic porphyritic rocks in a greenstone area, is not used here. If the igneous origin of the rock in question is in doubt there may be some justification for using this vague term, but the porphyritic acid dykes described from this area are undoubtedly igneous and are therefore referred to as "porphyritic dacite dykes".

Physiography

The main physiographic feature of the area is the Phillips River which has cut its valley in an uplifted peneplained surface represented by the tops of the hills to the west of the area. To the south and south-west the Eyre and Mt. Barren ranges rise above this general level, as also does the Ravensthorpe Range to the east. The valley of the Phillips River is broad and symmetrical over the gneiss and granodiorite but narrows as it crosses the greenstone belt developing an asymmetric cross-section with low cliffs on one side.

The course of the Phillips River and its tributaries is strongly influenced by the geology of the underlying rocks (see Plate 1). The change in direction of the Phillips just below the road crossing follows a swing in strike. The Twertatup Creek, flowing over the amphibolitic rocks has cut a stream channel whose level of drainage is lower than the less developed streams to the north which flow over gneiss. It has thus captured several tributaries of these latter streams. The quartz dolerite dykes weather more rapidly than either the granitic rocks or the amphibolites, so that stream channels are often localised along them. The best example of this is Big Creek, which follows such a dyke for over a mile as an "old" meandering, aggrading stream between abruptly rising hills of gneiss.

The Manyatup Creek follows a remarkable serpentine course with high cliffs around the "U"-shaped bends of the meanders.

The amphibolites are covered by a red-brown to brown loamy soil which is in marked contrast to the sandy soil which overlies the granitic rocks. Rock outcrop is generally restricted to the stream channels.

Regional Distribution and Geological Structure

The area under consideration (see Plate 1) consists essentially of a sequence of amphibolitic meta-volcanic rocks, which occupy a NE.-trending belt 1-1½ miles wide. It is flanked to the north-west by a narrow band of schists (with associated crushed and laminated rocks) which separates the belt of volcanics from a complex of granitic gneiss and migmatites. To the south-east the volcanic sequence is terminated by intrusive granitic rocks, the contact between the two striking approximately 40°.

The gneissic complex, which is probably the granitized counterpart of a folded sequence of meta-sediments, continues for at least three miles to the north-west. It is probably continuous with the gneisses which extend far to the north and west of the area and which also appear on the south coast at Hopetoun. In the north-east a well-defined band of basic migmatite within the gneiss strikes north-west and occupies the north-east limb of an anticline which plunges in the direction 110°-130°. On nearing the band of schists the structure swings to 10°-20° parallel to the strike of these rocks, still maintaining the same lineation. The strike then remains similar for at least 1½ miles to the south-west. The central expanse of gneiss, as exposed in the Phillips River north of Cocanarup, lacks any reliable structural information. In the south-west corner of the area basic lenses within the gneiss again show a west to south-west strike and the same south-east plunging lineation. The overall structure in these rocks, as discernible from this scattered information, is a south-east plunging anticline, the nose of which somewhat abruptly abuts the band of schists.

North-east of Cocanarup the schists are predominantly meta-sedimentary, but to the west some are more basic and probably meta-igneous. The meta-sedimentary schists are relics of a far grander pre-gneiss sequence which extended to the north-west in the area now occupied by the gneiss. Drag folds indicate that the beds are the "right-way-up", with an anticlinal complex to the north-west which plunges south-east.

The trend of the schists approximately parallels a zone of crushed and laminated rocks which possibly indicates the proximity of large-scale faulting. This zone strikes 10°-15° east of the Phillips River, swings west-south-west south of Cocanarup and continues with a south-west strike as it cuts the upper reaches of Twertatup Creek. No reliable structural information was observed to indicate relative movement in this zone except a series of left-hand drag folds in schists within the zone of anomalous lineation to be mentioned below. A poor lineation at (175N, 135E)* suggests that in the north-east the movement is probably either east block north and down or east block south and up. Although the structure in the gneiss swings abruptly parallel to this zone, such a change in strike is not due to faulting as the lineations of the whole gneissic structure are constant, paralleling the fold axes (110°-130°). It is likely, however, that both folding and faulting are approximately synchronous, both affording a release of the prevailing stresses.

The majority of lineations in the schists conform to the regional south-east lineation of the gneiss except in the area south of Cocanarup. Here the normal north-east strike and south-east dip locally assume a south-east to east strike, with a south-west to south dip. Several different lineations are observable but one plunging in the direction 200°-210° is noticeably constant. In view of the fact that the regional fold structures plunge in the direction 110°-130°, these anomalous strikes and lineations are not related to the general fold pattern. They are most probably the result of localized drag on a fault zone. Such a fault would need a horizontal south block east component which indeed is suggested by numerous left-hand drag folds in this area.

Several observed strikes and lineations, e.g., those just north of the road in the Phillips River channel (7S, 4W), are not easily explained by such a simplified account of the deformation, and probably indicate the presence of other complexities in this highly deformed locality.

Overlying the schists is the main belt of volcanics. The name "Phillips River Meta-volcanics" is proposed for this sequence. It is well exposed in the Phillips River from (40S, 10E) to the contact of the granite at (80S, 125E). It consists predominantly of basic amphibolitic lavas and agglomerates with minor intercalations of meta-sedimentary lenses and more acidic volcanics. It is approximately 1.3 miles in thickness in this area. It is a typical complex basic volcanic pile with some dykes, sills and lenses of medium to coarse-grained hypabyssals, which represent the feeders for the later flows.

As the sequence is without any reliable marker horizons structural information is difficult to obtain. Such as is available, principally from small meta-sedimentary bands, shows that this accumulation of competent flows and sills and less competent agglomerate and meta-sedimentary horizons, has been strongly deformed by folding about a south-east plunging axis similar to the folding of the meta-sediments to the north-west. The general strike is east-north-east to north-east but, as would be expected,

*Co-ordinates on Plate 1 are in chains measured from a point 5 chains north of the Phillips River crossing.

it is somewhat variable and, due to the complex nature of the folding, is of little value in the structural interpretation. Poor outcrop conditions prevent any reliable co-ordination of the individual amygdaloidal and agglomeratic bands and even such localised features as the amygdaloidal tops of flows are too poorly exposed to allow any interpretation of sequence in the rocks concerned.

In the south-east corner of the area under discussion a magmatic granodiorite intrudes the Phillips River Meta-volcanics along a contact which trends approximately 40°. The contact is slightly discordant to the 10° strike of the adjacent volcanics [see in Manyatup Creek (50S, 145E)], and the dip of the flow layers (60°-70° NW.) parallel to the contact is in marked contrast to the east to south-east dip of these rocks.

The granodiorite and the Phillips River Meta-volcanics are cut by a set of basic dykes which are now represented by massive amphibolites, practically indistinguishable in hand specimen from the hypabyssal phase of the earlier volcanics. When exposed in the Manyatup Creek they trend north-north-east to north-east and are easily confused with the xenoliths of the older lavas, although they are more massive and show chilled edges grading into a coarser centre. Some have a fairly shallow dip to the north and in vertical sections are easily distinguished from the more steeply dipping xenoliths.

Eight and three-quarter miles to the north-east, in the granodiorite of Cattlin Creek near Ravensthorpe, identical dykes have been mapped (Fig. 5). Here it is clear that the magma has come in along joints in a chilled granite. The general strike in this locality is south-east (Woodward *et al.*, 1909, p. 14).

In the meta-volcanic rocks these amphibolite dykes are very difficult to distinguish from the older rocks, especially the coarser-grained hypabyssals. They are well-developed in the bed of the Phillips River between (65S, 85E) and (40S, 110E). Striking about 40° they are the predominant rock exposed in the river channel for over 30 chains. The nature of this occurrence is shown in Fig. 6. Multiple intrusion has added to the general complexity of the emplacement.

The granodiorite and the meta-volcanics in the Manyatup Creek are cut by several dykes of porphyritic dacite. In a well-exposed outcrop at (80S, 152E) a dyke striking 320° is seen cutting the amphibolite dykes in the granodiorite. No definite field relations have been observed between these intrusions and the pegmatites or the quartz dolerites, but it is considered most probable that these dacitic dykes are closely related to the post-granodiorite amphibolite dykes and are thus pre-pegmatite and pre-quartz dolerite.

Pegmatites are common throughout the area under consideration. By far the most important of these are the sheet-like tourmaline- and muscovite-bearing pegmatites which are found throughout the belt of volcanics. Varying from a few inches to several feet in thickness they probably fill horizontal joints produced by the release of vertically-acting stresses. Within the gneiss diverse types of pegmatite dykes and sills occur. They are devoid of the tourmaline and muscovite of the abovementioned, but may be biotitic.

Prominent quartz dolerite dykes, with coarse quartz gabbro or quartz diorite centres are the youngest intrusives in the area. At (76S, 68W) in Twertatup Creek, parallel quartz dolerite dykes are clearly seen to cut an older pegmatite sheet. The dykes usually follow a well-developed east-north-east trend. More rarely the outcrop may follow an irregular course, as, for example, at (70S, 90W) where the magma seems to have been emplaced in two sets of intersecting joints. The dykes occur in the gneiss, the meta-volcanics and the granodiorite.

Younger sedimentary cover is almost entirely absent from the area, except for an occasional occurrence of lithified river conglomerate or ferruginous grit. Conglomerate is best developed in the valley of Big Creek, while a small development of jointed grit occurs at (45S, 145W) in a small stream channel. Scattered boulders of a similar grit are found in the sandy soil which covers the gneiss at half a mile north-east of the crossing of the Phillips River and the Ongerup road.

Petrology

Meta-Sediments

These rocks are best developed in the north-east where they form a narrow belt between the gneiss and the main belt of meta-volcanics. Minor occurrences are found interbedded with the meta-volcanics. Generally they are schistose and show rapid mineralogic variation at right angles to the strike—a feature indicating their sedimentary parentage.

TABLE 1 — *Chemica iand Mineralogical Characteristics of the Meta-Sediments*

Group	Principal component oxides	Essential Minerals
1	(FeMg)O	Grunerite, magnetite, hematite
2	(FeMg)O, Al_2O_3	Anthophyllite, cummingtonite, chlorite, garnet, cordierite
3	(FeMg)O, Al_2O_3, $(Na_2Ca)O$	Anthophyllite, cummingtonite, cordierite, plagioclase
4	(FeMg)O, Al_2O_3, $(Na_2Ca)O$, K_2O	Garnet, staurolite, biotite, andalusite, plagioclase
5	(FeMg)O, Al_2O_3, $(Na_2Ca)O$, K_2O, CaO	Garnet, biotite, hornblende, plagioclase
6	Al_2O_3, $(Na_2Ca)O$, K_2O	Sillimanite, muscovite, plagioclase
7	Al_2O_3, K_2O	Sillimanite, muscovite, microcline
8	Al_2O_3, $(Na_2Ca)O$, CaO	Plagioclase, epidote, calcite

Note.—All groups are saturated with respect to silica and quartz is a common constituent of all assemblages.

A summary of the essential minerals which constitute these schists (Table 1) serves to indicate the variation in mineralogy resulting from variation in the chemical composition of the original sediments. To further emphasize this variation, the rocks have been grouped according to their component oxides, each group being treated separately in the summary descriptions that follow. All of these rocks are either saturated or over-saturated with respect to silica.

Group 1 is represented by lenses of highly contorted banded iron-rich rocks. They represent lenses of banded ferruginous chert in the original sedimentary successsion. Most of their complex contortions are secondary and due to tectonic deformation.

It is somewhat more difficult to describe the parent sediment of the rocks of Group 2. They are very rich in iron and magnesia with or without considerable alumina. The ratio Mg/Fe is probably very high. They could be conformable basic intrusives. The fact that sediments, rich in iron, magnesium, alumina and silica, without appreciable calcium and potassium are very rare today, and indeed in all post-Cambrian stratigraphy, does not necessarily mean that such sediments could not occur in the peculiar environments of the Pre-Cambrian. The formation of cordierite probably requires a high magnesium/iron ratio as well as sufficient alumina, but its occurrence so close (within 20 yards) to rocks of "high stress" metamorphic facies throws some doubt on the validity of the stress and anti-stress sub-division of metamorphic minerals, in particular the supposed anti-stress nature of cordierite. The chlorite of these rocks is a relict mineral and not due to retrogressive metamorphism so that within a chain or so of sillimanite grade metamorphism we apparently have disequilibrium with a low grade metamorphic mineral surviving as a stable relict.

In Group 3, with the incoming of noticeable amounts of calcium, some of the alumina is fixed as plagioclase. In most of the meta-sediments the sodium is sufficient for all the combined calcium and alumina to form a stable plagioclase. In Group 8 where this is not so, epidote appears as a primary metamorphic mineral. Rocks of Group 3 occur as lenses within the basic lava sequence. Some might have close affinities with the non-amphibolitic meta-volcanics which are at times mineralogically identical. It is to be expected that transitional tuffaceous sediments will occur which could be included in both meta-sedimentary and meta-volcanic sub-divisions.

The characteristic of Group 4 is the availability of potash in a system otherwise containing only iron, magnesium, alumina and silica. This results in the development of biotite. When iron and magnesium are in excess of the potassium but not of the alumina, the ferro-magnesium aluminium silicates almandine and staurolite accompany the biotite. In specimen 34184** the alumina content is sufficiently high to enable a pure aluminium silicate to form even after the iron, magnesium, potassium and sodium-calcium oxides have been satisfied. This aluminium silicate is, however, andalusite and not kyanite, an anomaly which again suggests that the importance of stress, in determining the stable mineral assemblage in metamorphism, has been over-emphasized.

In Group 5 the calcium content is in excess of that required for the plagioclase so that the calcium enters the ferromagnesian alumino-silicates to form hornblende. As this excess calcium content increases hornblende becomes the principal ferromagnesian mineral and the rocks become amphibolitic.

Groups 6 and 7 are examples of highly aluminous meta-sediments. They contain practically no iron or magnesia but are correspondingly rich in potassium and alumina. Sillimanite, muscovite and microcline are typical minerals. If sodium and calcium are present, plagioclase enters the assemblage.

The particular conditions under which the potassium-aluminium silicates (microcline or muscovite) formed are obscure. Perhaps the alkalinity of the environment effects some control as also may the prevailing stress. Often, however, the microcline appears to be later than the mineral assemblage with which it is associated, suggesting that it is due to potash metasomatism.

Several rock types show notable effects of metasomatism contemporaneous with and later than the epoch of metamorphic recrystallization. In such rocks as 34187 and 34183 tourmaline is very abundant and must represent a noticeable influx of sodium and boron. This tourmaline is orientated parallel to the lineation of the rocks and must have grown under stressed conditions. Zoisite, which occurs in the former specimen, could also be of metasomatic origin. The possibility therefore arises that much of the muscovite and microcline may also be due in part to introduced material which has come in with the elements required for the tourmaline and zoisite.

It has already been assumed that those meta-sediments which have been grouped, have their differences in mineralogy mainly because of differences in their sedimentary parent rocks and that later chemical changes have been subordinate. If this were not so it is difficult to understand the preservation of such fine variations in mineralogic assemblages as are observed across the strike of the schists. Intense metasomatism tends to develop a homogeneous end product of simple mineralogy. However, it must be remembered that the gneiss is very close to the schists and even if the adjacent meta-volcanic sequence was not always in its present juxtaposition with respect to the gneiss (see later **Geological History**) at least the schists in part certainly were. This gneiss is the product of granitization, i.e., intense metasomatism, and some effects in the adjacent schists are to be expected. However, the nature and source of such metasomatism is obscure. The problem will be briefly mentioned again in the review of metasomatism in the area. It might be mentioned, however, that the gneiss is char-

**Catalogue number in the general rock collection of the Department of Geology, University of Western Australia.

acteristically low in potash so that microcline is extremely rare. Thus it is doubtful if the late metasomatic microcline of the schists can logically be related to the granodioritic gneiss.

With regard to the grade of metamorphism which has controlled the mineralogy of these meta-sediments we may note that most of the outcrops occur close to the gneiss, so that the high temperature (high grade) minerals such as sillimanite, staurolite, cordierite and andalusite would be expected. The metamorphism, however, may be synchronous with and not consequent on the emplacement of the granitic gneiss. The fact that "stress" and "anti-stress" minerals occur together, at times within the same rock, throws grave doubts on the importance of the stress factor in determining the stable mineral assemblage. The occurrence of relict chlorite in non-retrograde rocks interbedded with schists of high grade metamorphic assemblages illustrates, perhaps, how stable a relict mineral can be in a peculiar chemical environment such as is afforded by certain of the rock types.

The Phillips River Meta-Volcanics

This group of rocks is a typical metamorphosed volcanic pile, made up originally for the most part, of basic lava flows and agglomerates which have suffered considerable deformation and regional metamorphism producing a complex assemblage of amphibolites. Interbedded with these amphibolitic rocks are minor amounts of meta-volcanics which are not amphibolites, hornblende being very subordinate or absent. Meta-sedimentary lenses occur but are rare and very restricted in their development.

Associated with these basic extrusives are various representatives of the hypabyssal phase of the same magma which solidified in channels at depth.

In the vicinity of zones of faulting the massive amphibolitic rocks become very schistose.

(i) *Amphibolitic Meta-volcanics*.—The amphibolitic meta-volcanics which include meta-lavas, meta-agglomerates and meta-tuffs account for 95% of the eruptive rocks of this sequence. The abundance of amygdaloidal and agglomeratic structures gives positive evidence of the volcanic nature of these amphibolites. Although there is ample evidence, afforded by field observations of highly deformed bands and by thin section studies of micro-folding within individual specimens, that these rocks have suffered considerable deformation, macroscopic schistosity is very poorly developed.

In thin section the rocks are seen to have suffered almost complete recrystallization and a linear parallelism of the elongate amphibole is common. This parallelism is sometimes only an apparent linear structure, as the amphiboles may have their elongation parallel to a preferred plane but not to a line within that plane. A close macroscopic examination of specimen 34199 shows that the linear parallelism of the section is in fact only a planar parallelism. When the rocks are amygdaloidal and the amygdales are small, the amphibole may assume a pseudo-flow structure around the elongated cavity filling. This, however, is not a primary structure but due to the fact that, for the most part, the elongation of the amygdale and the parallelism of the amphiboles are tectonic in origin and both due to the same deformation. For example, the long axes of the elliptical amygdales in specimen 34274 are parallel to the tectonic lineation of the area, and as such this elongation is most probably a secondary structure.

The mineral assemblage developed in the groundmass of the meta-lavas belongs to the amphibolite metamorphic facies (Turner and Verhoogen, 1951, p. 446). Hornblende and plagioclase constitute 85% of the rocks, the minor associated minerals being quartz, biotite and cummingtonite with accessory sphene, apatite, iron ore and leucoxene.

The plagioclase, which is typically andesine, is of two types of which by far the most important is a clear, granular untwinned metamorphic variety. The other less important type is a relict igneous plagioclase still showing a tabular or lath-like form and complex lamellar-twinning so characteristic of plagioclase which has crystallized from a liquid phase. The metamorphic plagioclase is commonly reverse zoned.

The hornblende forms prismatic blue-green crystals which at times exhibit terminal overgrowths of a colourless lamellar-twinned cummingtonite. Where broad corroded remnants of hornblende are terminated by this cummingtonite (see Fig. 2) it is clear that the cummingtonite has been formed, at least in part, by replacement of the earlier hornblende.

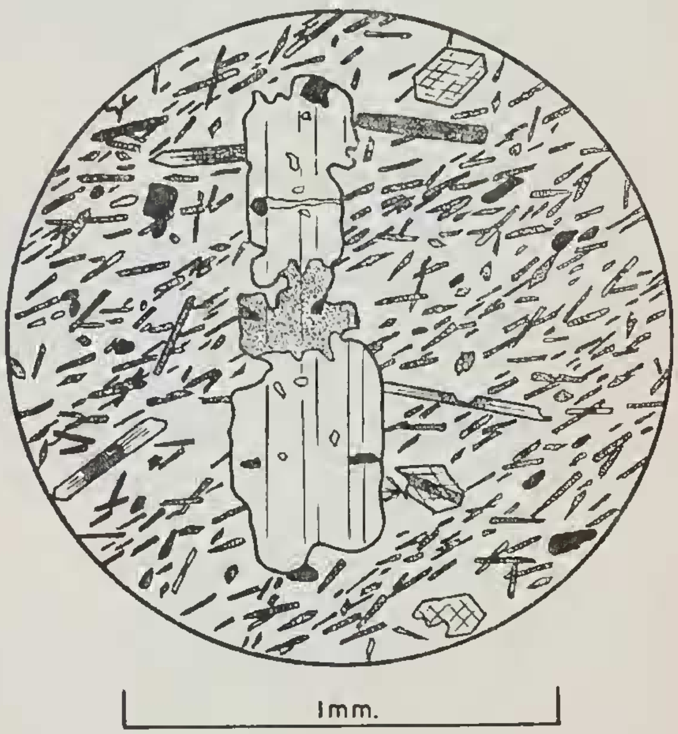


FIG. 2.—Sketch of a typical porphyroblast of cummingtonite centred about a corroded remnant of hornblende. Hornblende originally formed the greater part of the crystal but has been replaced by cummingtonite. The groundmass consists of a fine aggregate of granular plagioclase and prismatic hornblende, occasionally with cummingtonite overgrowths (specimen 34199).

The amygdales may consist of granular plagioclase, quartz, epidote and hornblende occasionally with accessory chlorite. Metasomatic cummingtonite, biotite, prehnite, epidote, clinozoisite and chlorite are occasionally present in the groundmass.

The agglomeratic rocks exhibit a mineral assemblage similar to the groundmass of the lavas both in the fragments and the matrix with the exception that biotite and quartz are somewhat more common and in highly calcareous types diopside and calcite make their appearance.

The texture of the meta-volcanics is invariably one of fine grain (< 0.05 mm.) with the untwinned plagioclase and quartz forming a granular mosaic in which a greater or less amount of blue-green, prismatic or acicular hornblende (and more rarely colourless cummingtonite) is embedded. Occasionally the amphibole assumes more prominent dimensions especially when due to the recrystallization of amygdale fillings. As in the meta-lavas, hornblende at times exhibits a corroded form with or without cummingtonite overgrowths.

It is important to note that the recrystallization has not generally been accompanied to any extent by an increase of grain size, so that the original fine texture of the groundmass and very small primary structures are still preserved. However, nearly all trace of the original mineralogy and mineral inter-relationships has been destroyed. One exception is the relict plagioclase phenocrysts previously mentioned.

Metasomatism must have been important in many ways during the metamorphic history of the meta-volcanics. Besides the abovementioned late cummingtonite replacement there is other evidence of changing chemical environments. The reverse-zoned plagioclase is evidence of partial adjustment to an environment being enriched in calcium and aluminium. The biotite, muscovite, tourmaline and chlorite of certain specimens are probably metasomatic in origin and related to nearby pegmatite sheets. Many peculiar epidote-rich rock types are evidence of calcium-hydroxyl metasomatism. For example, an agglomerate (34211) which still shows its original textures and structures has been completely reduced to a quartz-epidote aggregate.

(ii) *Non-Amphibolitic Meta-volcanics.*—These rocks have a minor distribution within the basic meta-volcanics. Some probably represent acidic lavas, and others were agglomeratic or tuffaceous sediments. The calcium, iron and magnesium content has been sufficient to produce hornblende in very minor amounts only, if at all. Non-volcanic meta-sediments occur with very similar mineralogy. The meta-volcanics are distinguished from the meta-sediments by the presence of typical agglomeratic structures and relict igneous plagioclase crystals the latter indicating that the rock was either a porphyritic lava or a crystal tuff.

The mineralogy clearly shows that they are chemically richer in the alkalies, alumina and silica than the normal amphibolitic meta-lavas, but correspondingly poorer in calcium, iron and magnesium. Like their amphibolitic counterparts they are fine-grained and their mineral assemblage represents a sub-facies of the amphibolite metamorphic facies (Turner and Verhoogen, 1951, p. 446). The plagioclase still persists in its two forms, namely, as untwinned relict igneous crystals and the more abundant granular untwinned metamorphic type.

Two varieties of cummingtonite of different origin are present. One type is that which has developed as the original amphibole during the metamorphic recrystallization. This is the cummingtonite comparable with that of the meta-sediments. The other type is represented by the overgrowths on hornblende in specimen 34220. Hornblende clearly was the amphibole which resulted from the recrystallization of the parent rock, but a subsequent change in the chemical nature of the environment (an enrichment in iron and magnesium relative to calcium and aluminium) resulted in a stable cummingtonite overgrowth. As in the amphibolitic meta-volcanics, some of this cummingtonite may have been developed by replacement of the earlier hornblende.

Late calcium metasomatism is evident from the calcite replacement veins in several rocks. The resorption of the hornblende in specimen 34220 is also a late metasomatic phenomenon.

(iii) *Associated Hypabyssals.*—Within a pile of five to seven thousand feet of basic lavas some associated basic hypabyssal representatives are to be expected. These, in the form of dykes and sills, represent that portion of the magma which solidified in channels and concordant offshoots below the surface of the accumulating volcanic pile. They may or may not be chilled against the country rock, and in either case the relations with the lavas are complicated and obscured by the strong deformation which the whole sequence has undergone. Contacts are often somewhat sheared.

Thus irregular pods, dykes and sills of coarse-grained amphibolite are commonly found in the fine-grained amphibolitic lavas and agglomerates, folded but less severely crumpled than the more incompetent members. Since it has been shown that all the meta-lavas are fine-grained (increase in grain size by recrystallization being a very rare and unimportant phenomenon), these hypabyssals are easily distinguished from their extrusive counterparts. However, it is impossible to trace field relationship for any distance under the prevailing conditions of outcrop. Also, great difficulty is experienced in macroscopically distinguishing these rocks from the later suite of post-granodiorite amphibolitic intrusives.

Mineralogically they consist of tabular blue-green hornblende and plagioclase which varies in composition from andesine to bytownite. The plagioclase in part forms large tabular lamellar-twinned crystals which are igneous in origin and clearly indicate that the coarse texture of these rocks is primary and not the result of metamorphism. As in the fine-grained meta-lavas, granular untwinned plagioclase (the product of recrystallization) is present and is a useful (though not infallible) guide in distinguishing these coarse-grained amphibolites from the genetically distinct amphibolites which intrude the granodiorite.

It should be noted that any hypothesis concerning the genesis of the coarse-grained amphibolites that assumes all these rocks are approximately the same age is completely disproven by field evidence in the granodiorite exposures of the lower Manyatup Creek. At (80S, 153E) folded xenoliths of the Phillips River Meta-volcanics contain patches of coarse-grained amphibolite, which, by virtue of their relict igneous plagioclase and texture cannot be explained by "metasomatic coarsening". They are not chilled against the enclosing rock. Then, cutting the granodiorite and these xenoliths are the irrefutably later amphibolite intrusions (see Fig. 8).

(iv) *Schistose Amphibolites.*—In the vicinity of zones of rock failure the characteristically massive basic rocks of the Phillips River Meta-volcanics pass into amphibolitic schists. Thus the schistose members of this sequence are particularly localized along the zone marginal to the gneiss and to a lesser extent in a zone striking south-west in Twertatup Creek between (50S, 45W) and (90S, 85W).

The catalytic influence of the increased deformation and the availability of solutions in these zones has promoted some increase in grain size, although some very coarse schists are probably the result of shearing of originally coarse-grained amphibolites.

These schistose rocks are frequently veined parallel to the schistosity with diopside-rich material. In such veins the hornblende of the original schist is replaced by diopside which is occasionally associated with talc, epidote, calcite and prehnite. The veining is the result of subsequent metasomatism. With diopside being the main constituent of the veins and forming at the expense of hornblende, some relative enrichment in calcium must have taken place. This may have been effected either by the introduction of this element or by the removal of magnesium, iron and aluminium. The diopsidization could be an earlier high temperature metasomatic phenomenon which was followed by the introduction of carbon dioxide which produced a form of steatitization giving talc and epidote from the diopside (Turner and Verhoogen, 1951, p. 494).

In specimen 34231 where the formation of the diopside veins similarly requires an enrichment in calcium the plagioclase in the vein has become more sodic during the metasomatism. Evidently, under the prevailing physico-chemical conditions, oligoclase was the stable plagioclase in lieu of andesine.

(v) *Summary of the Petrogenesis of the Phillips River Meta-Volcanics.*—The complex is the result of the regional metamorphism of a volcanic pile consisting of 95% extrusive rocks, 95% of which are basic in composition. Intercalated with these basic members are minor developments of more acidic volcanics richer in sodium, alumina and silica than the normal rock types and thus equivalent to the sodic differentiate of the basic magma. Relict amygdaloidal and agglomeratic structures, together with blastoporphyritic textures give conclusive evidence of the volcanic nature of these rocks.

The mineral assemblage is typically hornblende and plagioclase with minor amounts of biotite, cummingtonite, quartz, epidote, diopside, sphene, apatite and iron ore. Quartz, biotite and diopside are more common in the meta-sedimentary fragmental volcanics.

The plagioclase is usually andesine and may even be more calcic. It is of two varieties—relict igneous plagioclase crystals, which are tabular or lath-like in habit and show lamellar-twinning, and metamorphic plagioclase (by far the most abundant) which is granular and untwinned. The latter is often reverse-zoned, which is evidence of the environment being metasomatically enriched in calcium. Other evidence which leads to this same conclusion is the calcite replacement in the meta-dacites and the diopside, prehnite, and carbonate veining, which is common to most rocks of the sequence.

Coarse-grained hypabyssal counterparts of the basic lavas occur and are easily distinguished from the fine-grained volcanics by the difference in grain size which is very similar to that originally developed in the parent rock.

The whole sequence has suffered very strong deformation which has been more severe in the less competent agglomeratic and sedimentary bands than in the competent intrusives or thick lava sequences. The latter rocks remain fairly massive in structure. Near zones of shear all these rock types pass into schists.

Besides the calcium metasomatism there have been other similar replacement phenomena. One is the replacement of amphibolitic volcanics by epidote. Another is the replacement and overgrowth of cummingtonite on hornblende. This cummingtonite is later than the epoch of recrystallization and is probably of later genesis than the cummingtonite of certain meta-sedimentary and agglomeratic bands which, because of their original chemical nature have given cummingtonite directly.

Crushed and Laminated Rocks

Several zones of crushed and laminated rocks occur within the schists which flank the Phillips River Meta-volcanics to the north-west. These rocks display parallel, lenticular and banded structures so typical of rocks in which strong lateral movements have been localized. One such zone strikes 15° between (170N, 135E) and (35N, 70E). The crushed rocks are very fine-grained, finely banded, with augen and micro-lenticular structures which give the rocks an apparent "flow" structure (34235). Mineralogically they consist principally of fine granulated quartz with muscovite, biotite and a little plagioclase. The plagioclase may be as basic as labradorite. Immediately adjacent to these crushed rocks in the above zone are very finely laminated rocks which consist of hornblende, plagioclase and quartz. The laminated nature of these rocks is due to the segregation of the dark hornblende and the colourless quartz and plagioclase into distinct bands. In one outcrop of this type of rock 19 such bands were present within 1 cm. In such a finely banded specimen (34236) the plagioclase is a bytownite though generally the plagioclase is less calcic, being either andesine or labradorite.

Other zones of crushed rocks trend north-east to south-west through (65S, 115W); from (10S, 00W) in the Phillips River for half-a-mile in a west-south-west direction; and in the Twertatup Creek at (75S, 65W) along a 35° strike.

The fine-grained crushed rocks, with their parallel and lenticular structures are due to rock failure and strong shearing movements localized along zones within the meta-sediments but probably slightly discordant to their strike. Such deformation has taken place at a high temperature so that the movement parallel to the foliation has produced a fine gneissic "flow" structure rather than excessive mylonitization of the constituent minerals.

The proximity of the laminated and schistose rocks to such a zone has been noted. There appears to be no doubt that the laminated nature of such rocks which are in juxtaposition to crush-zones, is due to a process of metamorphic differentiation under the influence of strong shearing movements, rather than to original sedimentary stratification. It is thus a pseudo-stratification which parallels the schistosity and not the bedding of the original rocks.

The production of the pseudo-stratification is broadly synchronous with the deformation of the rocks and is the result of the unmixing or differentiation of the deformed rock mass into assemblages of minerals which respond similarly to the prevailing stresses. Thus, by means of direct componental movements, involving mechanical gliding or rotation of mineral grains, and indirect componental movements which include solution, diffusion and redeposition, the more mobile quartz and plagioclase are separated into bands apart from the hornblende which is mechanically dissimilar (Sander, 1930, pp. 115, 269-275, quoted by Turner, 1941, p. 12).

The preservation of minerals, such as calcic plagioclase, in these rocks, and the completeness of this differentiation is evidence of the very high temperatures prevailing at the time of deformation.

Granodiorite

The granitic mass which cuts off the Phillips River Meta-volcanics to the south-west is continuous with that which forms the centre of the complex in the vicinity of Ravensthorpe townsite. The contact with the volcanic succession, as exposed in the lower reaches of the Manyatup Creek, is slightly transgressive to the strike of these older rocks. Over much of the area where this rock is developed there is a well-defined flow-banding due to the orientation of the ferromagnesian minerals and basic xenoliths. This structure is approximately parallel to the contact and dips 60° to 70° north-west which is strongly transgressive to the east-south-east dip of the meta-lavas. Although the contact is obviously discordant, no reliable evidence of a chilled margin against the country rock has been observed. There certainly is no evidence of it within $\frac{3}{4}$-chain of the contact at (50S, 145E).

Most of the mineralization of the Ravensthorpe area is marginal, and probably genetically related, to the granodiorite. The granodiorite consists of oligoclase (45%), quartz (30%) and hornblende (25%). The most important petrographic feature is the blue-green hornblende which occurs as very disjointed crystals. When viewed normal to the *c* axis small parallel orientated disconnected prisms form an optically continuous crystal, or else the prism is seen to be notably sutured (see Fig. 3 (A)). When viewed in a section cut perpendicular to the c axis it is also very irregular with disconnected granules forming the basal section. The occurrence of flow-banding at the contact indicates the fluid nature of this rock at the time of its emplacement. However, it is not so certain that the final rock is the result of crystallization from a rock melt. A glance at the hornblende so typical of this granodiorite (see Fig. 3), with its disjointed crystal form, arouses immediate doubts as to its parentage. These irregular crystals could be the result of late magmatic resorption of primary hornblende or perhaps to some extreme form of poikilitic growth. Again, they could owe their form to post-crystallization recrystallization being modified under the influence of subsequent regional metamorphism. The occurrence of small acicular crystals of hornblende in the plagioclase in exactly the same way as in the relict plagioclase of the meta-volcanics does in fact suggest that this granodiorite has suffered some metamorphism.

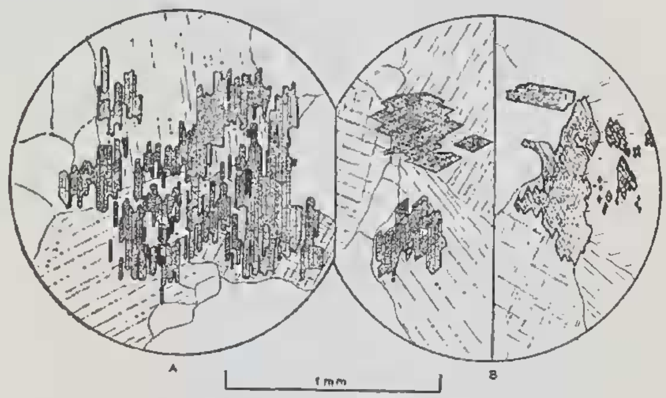


FIG. 3.—Sketch showing the appearance of the hornblende in the granodiorite when viewed (A) in a section parallel to the *c* axis (specimen 34239) and (B) in a section perpendicular to the *c* axis. The corrosion has been predominantly by the plagioclase. Quartz (clear) is the only other constituent.

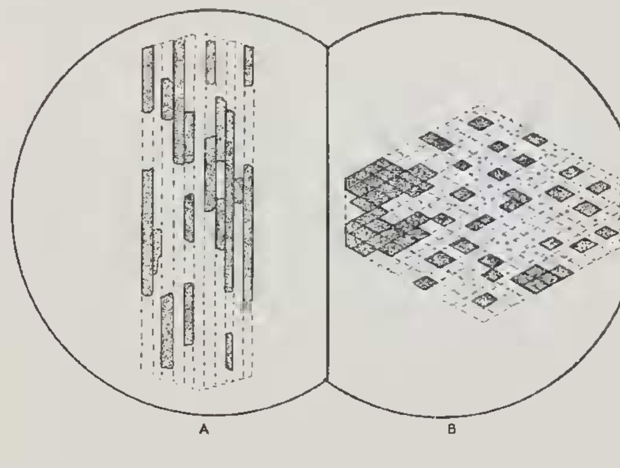


FIG. 4.—An idealized sketch illustrating the nature of the resorption of a hornblende crystal in the granodiorite, producing disconnected, yet optically continuous, fragments.

The clue, however, is given in small veins of granodiorite which cut coarse xenolithic amphibolite at (50S, 185E). In thin section these veins are very similar to the normal granodiorite except a little finer in grain and richer in quartz. Although they are definite vein offshoots of the granodiorite magma, there is no evidence of alignment of the minerals parallel to the margins, nor is there any chilled margin. Their formation is due entirely to the replacement of the original hornblende of the amphibolite by plagioclase with or without quartz. The resorption of the hornblende has been controlled to a certain extent by its cleavages, so that relict fragments are bounded by cleavage faces rather than normal crystal faces, as they would be if they resulted from crystallization. The resorption of the hornblende has been easier parallel to the c axis and more difficult at right angles to the cleavages, so that individual cleavage columns have been removed, leaving adjacent columns untouched. This preferential corrosion parallel to the c axes along cleavage columns thus ideally produces an optically continuous basal section made up of disconnected cleavage rhombs, and when viewed in the prism zone, an aggregate of orientated prisms, again disconnected in the section but optically continuous (see Figs. 3 and 4).

When the relict hornblende in these veins is compared with the disconnected crystals of the typical granodiorite it is found that they are identical. The fragmentary nature of the hornblende in the main granitic body is explained by exactly the same sort of corrosion of originally larger crystals often leaving as relics, cleavage columns, bounded by cleavage faces.

On this evidence it is suggested that although the plutonic body was intruded in a magmatic state, it is the result of metasomatism of amphibolitic rocks in which the hornblende is replaced by plagioclase and quartz. Such metasomatism would be the result of the introduction of silica, alumina, sodium and sometimes calcium, and expulsion of iron, magnesium and sometimes calcium.

Just how far the magma has moved is conjectural. The fact that the sieve-like hornblende crystals have not been disrupted (the fragments remain in optical continuity) suggests that the movement has not been excessive or at least has been a very quiet injection.

One important point which is not so clear is what is the result of the granitization of the fine-grained lavas? The production of the large areas of ophitically continuous relict fragments is only possible when the original rock has a fairly coarse texture. Further work on this interesting pluton will be necessary to determine the relative contribution of the replaced coarse—and fine—grained amphibolites to this magma. Unless recrystallization to a coarse-grain precedes resorption, the latter amphibolites will give a rock of different texture to the former. There does not seem to be any evidence of the granodiorite producing any recrystallization of the wall rock with the production of uniformly large crystals. Relatively fine-grained xenoliths have been noted which exhibit no noticeable increase in grain size.

The unorientated acicular hornblende inclusions in the plagioclase of specimen 34239 present another problem. They appear to be typically secondary and identical with inclusions in the relict plagioclase of highly metamorphosed volcanics and associated hypabyssals, e.g., specimens 34196 and 34224. It is possible that under sustained conditions of elevated temperatures and stress, some metamorphic or metasomatic introduction or redistribution took place with the growth in the plagioclase of these secondary acicular crystals.

Amphibolite Dykes of Post-Granodiorite Age

Woodward (1909) has recorded the occurrence of north-north-west-trending amphibolite dykes in the granitic rocks which form the core of the Ravensthorpe-Kundip complex. During the present investigation these dykes were examined in Cattlin Creek near Ravensthorpe and the relations of one of these intrusives to the granodiorite was mapped in detail (see Fig. 5). The chilled margins of the dykes and the angular nature of the contacts clearly show that the basic magma has been injected into joints in the chilled granodiorite.

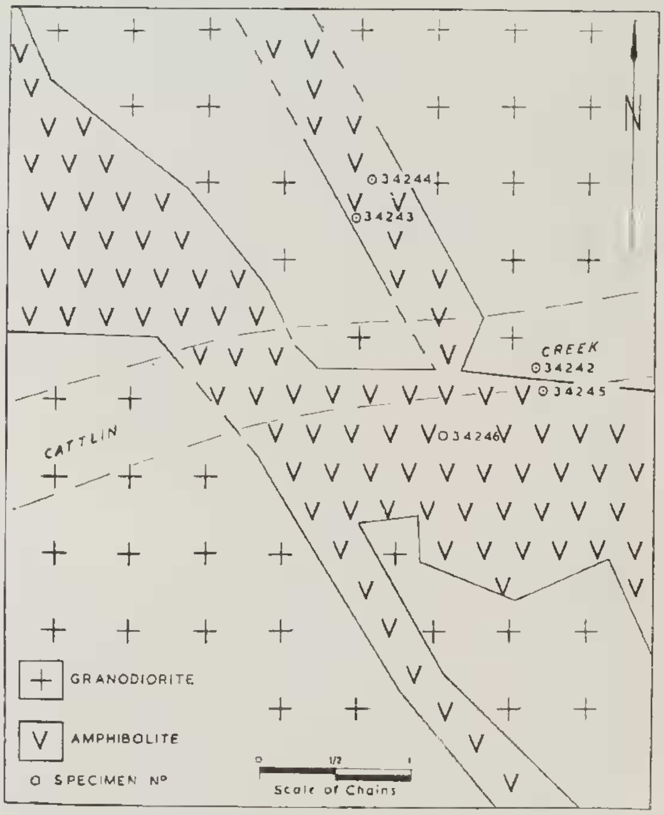


FIG. 5.—Amphibolite dykes in granodiorite in the Cattlin Creek, Ravensthorpe, 20 chains upstream from the south-west corner of M.H.L. 58.

Similar dykes occur in the Cocanarup area. In the granodiorite of the Manyatup Creek they are fairly easily recognised, although some xenolithic material is at times very similar. They strike north-east.

Within the belt of meta-volcanics the best exposure of these dykes is in the Phillips River at (53S, 100E). Here the occurrence is complicated by multiple intrusion. Figure 6 illustrates this complexity. Xenolithic agglomerate is included in a coarse-grained dyke over 12 chains wide, whose marginal contacts are not exposed. This dyke is in turn intruded by dykes of small size which are genetically related to the main intrusion and petrologically very similar, especially in the chilled marginal phase.

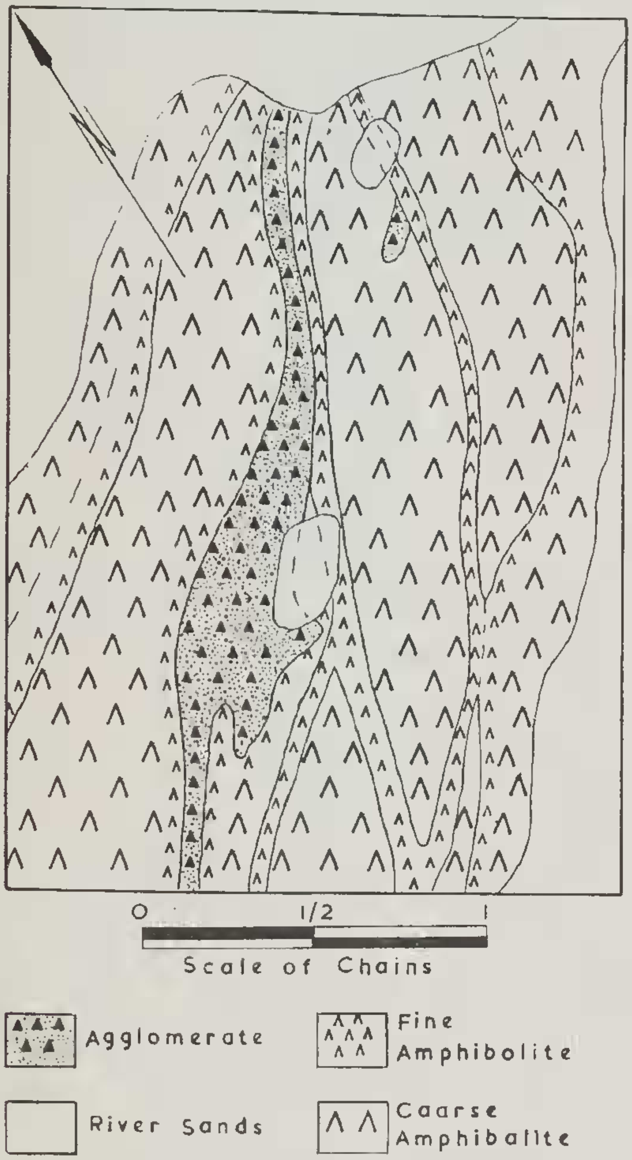


FIG. 6.—Plan of a complex occurrence of the amphibolites in the channel of the Phillips River at (53S, 100E).

Mineralogically they consist of plagioclase (labradorite or andesine) in tabular, lamellar-twinned crystals which are clearly igneous in origin and tabular blue-green hornblende. The plagioclase crystals are commonly kaolinized. Granular plagioclase is usually absent but occasionally occurs, chiefly in restricted veins. Skeletal ilmenite is a common accessory.

These rocks are the equivalents of basic dykes, probably tholeiitic in character, which were intruded into the Phillips River Meta-volcanics and the granodiorite after the main period of folding and metamorphism. Conditions prevailing after their emplacement caused hornblende to replace the original ferromagnesian constituents. This replacement is complete, even in the chilled margins, and has produced an amphibole indistinguishable from the normal hornblende of the highly metamorphosed earlier amphibolites. It is clearly not the result of deuteric alteration. The hornblende pseudomorphs the earlier pyroxene which sub-ophitically included much of the original plagioclase. The plagioclase is now kaolinized.

In contrast to the hypabyssal phase of the earlier Phillips River Meta-volcanics these intrusives are better defined with sharp unsheared chilled margins against the country rock. The coarser phases have only kaolinized plagioclase. Granular feldspar, the product of recrystallization, is absent. However, in all three localities described, some granulose textures were recorded in certain finer phases. Then it is almost impossible to distinguish these rocks, either macroscopically or microscopically from the earlier intrusives. This occasional development of granulose texture, especially granular plagioclase, may be explained in part (if not entirely) by the localized activity of vein solutions. Under the influence of solutions, with elevated temperatures and pressures, localized minerals could recrystallize. This appears to be the only logical explanation of the veins of granular plagioclase in the typical non-granulose amphibolite dyke (specimens 34243 and 34244).

The Dacite Dykes

In the lower course of Manyatup Creek a dyke of porphyritic dacite (34252) cuts both the granodiorite and the amphibolite intrusives. It trends 140° and is well exposed at (75S, 152E). Macroscopically it is a light flesh-coloured rock, porphyritic, with phenocrysts of quartz and euhedral oligoclase, up to 4 mm. long, though averaging 1½ to 2 mm. Mineralogically the rock consists of oligoclase 60%, quartz 35% with accessory muscovite and biotite.

The dyke is the result of the injection of dacitic magma into fractures in the granodiorite (and probably elsewhere also in the volcanics). The magma may be genetically related to the basic magma which gave rise to the younger amphibolite dykes. Small amounts of dacitic differentiate are quite commonly associated with tholeiitic volcanism.

The Granitic Gneiss and Migmatites

Gneiss occupies the area to the north-west of the belt of schists and its associated sheared rocks. It extends for at least three miles in this direction and probably has a much larger development to both the north and west.

The contact of the gneiss with the schists is characterized by migmatites. This is especially the case where meta-sediments are absent from the contact zone and the gneiss passes through basic migmatite into schistose amphibolitic lavas. All the meta-sediments adjacent to the gneiss exhibit sillimanite grade metamorphism. A fine development of migmatites occurs in the north-east of the area. From (120N, 85E) it extends in a north-north-west direction for at least ¾-mile, following the strike of the gneiss. The rocks of this zone are very finely laminated, and the individual laminae have a remarkably constant attitude and extensive lateral development. Most of the gneisses are granodioritic with a granoblastic texture. The plagioclase is an oligoclase and forms tabular twinned crystals. Hornblende is the principal ferromagnesian mineral and occurs as corroded, granular, brown-green crystals which are in marked contrast to the prismatic blue-green hornblende of the meta-lavas and the disjointed crystal relicts of blue-green hornblende in the granodiorite.

The most significant feature of the gneiss is that, although much folded, any lineation in it has a constant trend (110° to 130°). This is explicable only if the greater part of the gneiss is a product of granitization which has produced the present granitic rocks from a pre-existing folded sequence without the production of an either wholly or partly liquid magmatic phase. Further, it is important to note that the lineation in the gneiss has similar trend and plunge to that in the adjacent schists and meta-volcanics. It is therefore logical to conclude, regardless of whether there has been any faulting marginal to the gneiss, that the rocks now represented by the gneiss were part of the same fold province as the Phillips River Meta-volcanics and sediments.

It remains to determine the nature of the rocks which have been granitized and the process whereby this change was effected. Were the original rocks predominantly a sequence of basic lavas and agglomerates comparable with the Phillips River Meta-volcanics, or were they essentially sedimentary, like the marginal schists along the contact in the north-east? Although the basic migmatite bands in the gneiss are probably the result of *lit-par-lit* injection and granitization in highly schistose amphibolitic meta-lavas, it seems likely that the greater part of the sequence was meta-sedimentary. It is difficult to envisage the preservation of a narrow basic band for over ¾-mile if it is only a relict of a once continuous basic succession. However, it is just what would be expected if narrow bands of basic lavas, which are difficult to granitize, are only minor intercalations in a sedimentary sequence which is relatively easily converted into a granitic rock.

The granitization process has been one which has left the area enriched in sodium, calcium, alumina and silica. Potassium is rare and is usually quite readily held in accessory biotite. The whole sequence has first been recrystallized, producing typical granular brownish hornblende. Much of the quartz is probably merely due to recrystallization under the influence of granitization, as also may be much of the plagioclase. On the introduction of the required solutions to effect compositional and textural changes, the granitic character of the rock, with its lamellar-twinned plagioclase, was developed.

Enrichment of certain rock types in silica is obvious from the study of the basic migmatite (34257) and hornblendic gneiss (34253, 34254). To produce the basic migmatite from a granulose basic rock quartz merely replaces the hornblende along bands parallel to the foliation. The corroded nature of the hornblende and biotite in the hornblendic gneiss is largely the result of quartz replacement (see Fig. 7).

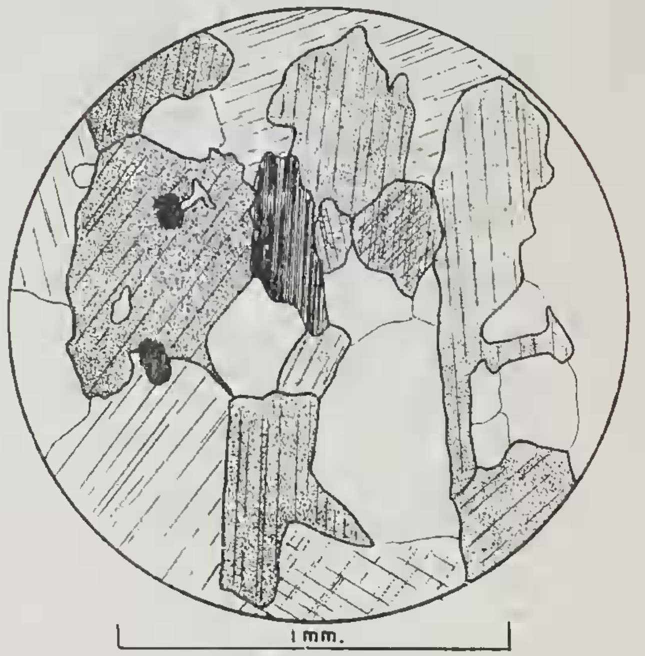


FIG. 7.—Sketch showing the granoblastic texture of a typically hornblendic gneiss. The hornblende crystals are notably corroded by quartz (clear). The other colourless mineral present is andesine. Biotite and magnetite are accessory minerals.

Pegmatites

There are many varieties of pegmatitic rock within the area mapped, but they can all be broadly subdivided into two groups:

(i) The dykes within the gneiss.

(ii) The dykes and sheets within the meta-volcanics and meta-sediments.

(i)—Within the gneisses various pegmatitic dykes and sills occur which consist of microcline, plagioclase and quartz, often with biotite and, more rarely, muscovite. They fill gash fractures and minor shears within the gneissic complex as well as sills in the migmatitic bands.

(ii)—Horizontal sheet pegmatites characterise the belt of meta-volcanics. They are more abundant than the pegmatites in the gneisses. They carry black tourmaline and have muscovite- or lepidolite-rich zones (34260). Biotite appears to be absent. Quite commonly there is a graphic quartz-microcline central zone (34261). The typical sheet-like bodies vary from a few inches to several feet in thickness. They probably fill fractures produced by the release of vertically-acting stress.

Quartz Dolerite Dykes (including the Quartz Gabbros and Quartz Diorites)

All the rocks in the area, with the exception of recent superficial sediments, are cut by a suite of basic dykes which have a general east-north-east trend. They vary from small fine-grained basaltic dykes a few inches wide to intrusions, 1 to 2 chains in width with gabbroidal or dioritic centres.

Detailed petrographic studies of many of these basic dykes throughout the area indicate that they may be subdivided mineralogically into two broad classes which, although differing a little in age are probably co-magmatic. The presence of transitional types between the two classes has made it impracticable to differentiate between the two types on a geological map. However, the characteristics of typical examples of both groups are set out below:—

Class 1.—(i) The pyroxene is a brownish-violet, bladed augite which may or may not be glomero-porphyritic.

(ii) The plagioclase is idiomorphic toward the pyroxene and forms large crystals sub-ophitically included in the augite.

(iii) The coarse-grained core is commonly dioritic (albitic plagioclase) deuterically altered, with hornblende replacing most of the primary pyroxene.

(iv) Multiple intrusions of small, later dykes varying from a few inches to a foot in width are common. Some of these intrusions are sodic differentiates of the principal dyke and often lead to epidotization of the adjacent dyke rock (34266). Others are mineralogically similar to the quartz dolerites of Class 2.

The type occurrence of this class is the dyke exposed in the Phillips River at (35S, 20E).

Class 2.—(i) The pyroxene is a colourless augite invariably forming equidimensional crystals in glomero-porphyritic aggregates.

(ii) The plagioclase forms only small lath-shaped crystals often ophitically included in the pyroxene.

(iii) The coarse-grained core is gabbroidal (plagioclase is labradorite) in which deuteric alteration (especially the conversion of pyroxene to hornblende) is only of minor importance.

(iv) Multiple intrusions, veining and epidotization are absent.

The type occurrence of this class is the dyke exposed in the Phillips River at (40S, 40E). In several localities, dykes with the features of Class 2 have been found cutting dykes typical of Class 1. The reverse age relationship has nowhere been seen.

In view of these facts it appears that during a period of mild tectonic disturbance the cooled, consolidated, complex of folded and granitic rocks was intruded by a suite of tholeiitic dykes along a set of east-north-east trending fractures. The earlier members suffered considerable deuteric alteration particularly in the coarse-grained, slowly cooled central core. The plagioclase became more sodic, even albitic, and hornblende with later actinolite and chlorite, replaced most of the earlier pyroxene. Prehnitization was also active in this phase.

A later suite of dykes, although derived from the same magma, usually had a slightly different mineralogy with a different variety of augite and less well-developed plagioclase. Deuteric alteration was much less important than in the earlier dykes, so that the coarse-grained core remained pyroxene-bearing and gabbroidal.

These basic dykes bear a marked resemblance to certain of the basic intrusions in the Stirling Ranges and at other localities along the south coast (Clarke *et al.*, 1954). Specimen 25327 from the Stirling Range is a spotted glomero-porphyritic, deuterically altered quartz diorite very similar to specimen 34265. Many of the unaltered augite dolerites have brownish or purplish titaniferous pyroxene similar to specimen 34263. It is very likely that many of these dykes belong to the same period of volcanism and are genetically related.

Superficial Deposits

The only sediments in the area which post-date the igneous and metamorphic rocks are isolated occurrences of ferruginous grit and river conglomerate. A well-lithified ferruginous grit, in part conglomeratic, forms a well-jointed outcrop overlying dolerite for some 2 to 3 chains along the creek bed at (45S, 145W). Specimens 34272 and 34273 are typical examples of this occurrence. The dominant constituent is rounded quartz, with some microcline, plagioclase, chlorite and muscovite. Specimen 34273 contains a few grains of granulated quartz, but it is mainly unstrained and with the microcline and plagioclase (andesine), is probably derived from the gneiss. This latter specimen is also conglomeratic with fragments of an earlier ferruginous grit and some fine-grained metamorphic quartz-plagioclase rock. A similar grit occurs as boulders over an area of gneiss at (15N, 35E).

Lithified river conglomerate is well developed in the channel of Big Creek. Magnesite, as a capping which varies from less than an inch to a foot or so in thickness is developed over certain basic rocks.

Review of Metasomatism

Reference has been made throughout the petrology to obvious replacements of one mineral by another and to the production of entirely new rock types by metasomatic processes. It is impossible to correlate each process and in most cases to postulate the source or nature of the introduced material. The various phenomena are mentioned below to indicate the complexity of the chemical changes of the environment of these rocks during the periods of folding, metamorphism and subsequent igneous intrusion. No certain chronological order can be given to the processes. They are summarily discussed in approximate order of importance.

Granitization.—The development of the gneiss was in part a metasomatic process whereby an original folded complex was converted *in situ* to a mass of granodioritic composition. Since the composition of the assumed sedimentary parent rocks is unknown, the precise nature of the metasomatizing agents cannot be postulated at this stage.

Production of the Granodiorite Magma.—A detailed study of the nature of the hornblende in the granodiorite has conclusively shown that this rock is not the product of crystallization from a rock melt, but is in fact the result of feldspathization and mobilization of older amphibolitic rocks. The process is one which demands the introduction of sodium and silica, with or without calcium and alumina.

Diopsidization.—A product of calcium metasomatism is seen in the diopside replacement veins which cut the amphibolites. Earlier hornblende is replaced by diopside. Similar phenomena have been recorded recently by Wilson (1953). Associated with some of this calcium metasomatism is some steatitization (carbon dioxide metasomatism).

Cummingtonitization.—The replacement of hornblende by cummingtonite is a proved phenomenon of metasomatism in many rocks. Simple late overgrowth cannot explain the relationship between these two minerals, as illustrated in Figure 2. The metasomatic process demands the replacement of the calcium, aluminium and alkalies of the hornblende molecule by iron, magnesium and silica. In some cases it seems to be a process localized along the contacts of basic dykes.

Biotitization (with or without the introduction of microcline).—The complete replacement of the laminated hornblendic rock (34236) by a biotitic rock has been observed in the field and is clearly seen in specimen 34237. Several occurrences of fine-grained biotite, quartz, microcline-bearing rocks identical with that of specimen 34237 are situated in this same zone of crushed rocks, so that this type of metasomatism (potash metasomatism) is probably quite significant in these localities. Much of the microcline of the meta-sedimentary schists may also be genetically related to the solutions which gave rise to this biotitization.

Although all this potash metasomatism is marginal to the gneiss, it does not seem to be genetically related to the granitization which gave rise to the gneiss. The gneiss is deficient in potash minerals. The solutions which produced the metasomatism probably found the schists, marginal to the gneiss, the easiest channelways and hence their effects are localized there.

Throughout the meta-volcanics, reverse-zoned plagioclase, zoned hornblende, epidotization, prehnitization and localized chloritization are but further evidence of the constantly changing chemical environment of the rocks discussed.

Petrological Correlation with the Rocks of the Ravensthorpe-Kundip Area

As mentioned in the introduction of this paper, one of the objects in carrying out the petrological investigation described above was to yield information concerning the relations and origin of the rocks of the Ravensthorpe-Kundip area which were mapped by Woodward nearly fifty years ago and petrographically described by Simpson and Glauert (Woodward *et al.*, 1909). Woodward in this early work subdivided the rocks of the district into:

Granite Series.—The intrusive granitic rocks which occupy the central and southern portion of the Ravensthorpe area.

Ravensthorpe Series.—The banded iron formation of the Ravensthorpe Range and the interbedded basic and ultra-basic schists.

Greenstone Series.—The amphibolites which occur north-west of the Ravensthorpe townsite and which extend south-west to just south of Cocanarup.

Kundip Series.—The gently-dipping quartzites, &c., which lie unconformably on the above series.

Of these rocks only the "Granite Series" and the "Greenstone Series" are represented in the area mapped during this investigation. The "Granite Series" is equivalent to the granodiorite of this report. The earlier writers correctly recognised the intrusive nature of this granitic body, and also its sodic character. They also correctly interpreted the amphibolite dykes as basic intrusions. However, the "Greenstone Series" was regarded as "a magmatic intrusion from which off-shoots have penetrated and shattered the granite" (Woodward *et al.*, 1909, p. 15). Sufficient evidence has been given above in the discussion of the Phillips River Meta-volcanics (to which these Greenstones are apparently equivalent) to indicate beyond all doubt that the series, as exposed in the Phillips River, is a metamorphosed volcanic pile, consisting largely of basic extrusive rocks. There is no evidence from the westward extension of this type section to indicate that the nature of the parent rocks has markedly changed, although their metamorphosed state may show minor differences. Thus, the amphibolite dykes are not off-shoots of some immense body of basic magma represented by the main amphibolite belt, but actually later dykes which cut both granodiorite and meta-volcanics which form this belt.

The "soda-granite" of the 1909 report is the granodiorite of this paper. The "kersantites" and "camptonites" of Glauert and Simpson (Woodward *et al.*, 1909) are no more than the recrystallized lavas and hypabyssals of the volcanic succession. They contain the same relict plagioclase phenocrysts, granular mosaic of plagioclase, blue-green hornblende and colourless cummingtonite (often as overgrowths on the hornblende). One thing that should be borne in mind, however, is that although such assumptions as the preservation of the original fine grain-size of the meta-volcanics, used in the interpretation of the complex assemblage of coarse-grained and fine-grained amphibolites are quite valid in the type area of the Phillips River Meta-volcanics, they may not hold throughout the whole greenstone sequence.

It is interesting to note that these early investigations petrologically subdivided the east to west or east-north-east-trending quartz dolerite dykes into two varieties. One of these was the "Quartz Diorites", the other the "Enstatite Diabases". These are respectively the Class 1 and Class 2 types of tholeiitic intrusions. However, although both types form equally large dykes, the earlier investigators only mapped the "Quartz Diorites". This may have been due to their failure to differentiate in the field the "Enstatite Diabases" from the "Quartz Diorites".

It is certainly due in part to the fact that many large intrusions of the former type were not recognized in the field. One such dyke, however, occurs in Cattlin Creek on M.H.L. 167 (31077-31088).

Regional Metamorphism

The original sequence of sediments and volcanics has been strongly folded and subjected to granitization to the north-west and to intrusion by granodiorite in the south-east during which a certain grade of metamorphism has been imprinted on the deformed rocks. Each of the above three processes has probably been effective to some extent in altering the mineral assemblages of the rocks. It is therefore not surprising to find it a difficult problem to interpret the metamorphic facies to which these rocks belong.

In particular, one feature which adds further difficulty to the problem is that most of the critical mineral assemblages which define the various metamorphic facies and sub-facies (Turner and Verhoogen, 1951, p. 434), are restricted to meta-sediments rich in alumina and silica. As is evident from the foregoing petrology, such rocks are rare in the area under consideration, and are restricted to a narrow band adjacent to the gneiss. Within the one mile wide band of meta-volcanics few such "metamorphic indicators" are present.

A further hindrance to the deciphering of the metamorphic facies within the area is the frequent evidence of lack of equilibrium within individual specimens. Metamorphic mineral assemblages are usually at equilibrium, but here, due either to the imprint of several unsustained metamorphic epochs or to metasomatism, zoning, partial replacement and other evidence of disequilibrium are abundant. The granular metamorphic plagioclase is commonly zoned. The hornblende of many of the amphibolites is not only zoned but partially replaced by cummingtonite. Biotitization, diopsidization and many lower temperature metasomatic phenomena are frequently developed.

Yet another important question must be fully understood before the regional metamorphism can be interpreted. That is, whether the gneiss and its adjacent meta-sediments are part of the same tectonic province as the Phillips River Meta-volcanics. This question will be considered again in the discussion of the geological history, but it might be mentioned here that there is strong evidence to suggest that the gneiss and its marginal rocks have not developed their structural, mineralogical and textural feature in their present position adjacent to the meta-volcanics and associated rocks.

(i)—*Evidence of Grade of Metamorphism from the Meta-Sedimentary Rocks.*—Of paramount importance are the sillimanite-bearing schists which occur at various localities marginal to the gneiss. Their restricted distribution is due partly to the fact that schists of the required chemical composition are only present in this zone, the one exceptional occurrence being the aluminous schists represented by specimen 34184 (meta-sedimentary Group 4). This aluminous rock, occurring half-a-mile from the gneiss at (40N, 110E), should contain sillimanite if the metamorphic conditions were favourable. Instead, staurolite and andalusite are present. It is likely, therefore that the sillimanite zone is in fact restricted to the region immediately adjacent to the gneiss.

A detailed examination of the meta-sedimentary schists at (50N, 85E) indicates that although sillimanite-bearing schists are present, the problem is confused by the occurrence of interbedded schists containing relict chlorite (34176, 34177) and "anti-stress" cordierite-rich rocks.

The small lenses of meta-sediment interbedded with the meta-volcanics generally have a mineral assemblage which is not diagnostic of any particular metamorphic sub-facies. They consist of plagioclase, biotite and hornblende, with or without garnet. The latter mineral is often rich in calcium and probably contains considerable amounts of manganese. As such, it is of little use as a zone-mineral. The one occurrence of a diagnostic zone-mineral in the volcanics is the staurolite of the previously-mentioned locality (34184). At least here the Phillips River Meta-volcanics have suffered metamorphism only slightly less intense than that of the sillimanite grade.

(ii)—*Evidence of Grade of Metamorphism from the Amphibolitic Rocks.*—In view of the fact that critical meta-sedimentary mineral assemblages are insufficiently numerous throughout the meta-volcanic rocks to indicate the grade of metamorphism of this important succession throughout its extensive development, it is essential to consider other means of assessing it. This is particularly the case since the known grade of metamorphism in the schists adjacent to the gneiss may have no relation to that developed in these rocks, i.e., if they are of a different province. Some definite information, obtained directly from the mineral assemblages of the amphibolites themselves would be invaluable. Unfortunately, the assemblage hornblende-plagioclase can exist with only minor modifications from the lowest garnet grade to the highest sillimanite grade. These minor modifications are changes in the type of plagioclase and hornblende which are stable under different conditions.

In the amphibolitic rocks of the Phillips River Meta-volcanics the plagioclase is zoned and thus not a member of a system in equilibrium, but it is commonly an andesine [and in several instances is even a bytownite or anorthite (34224, 34236)]. The plagioclase, therefore, indicates that the grade of metamorphism of the meta-volcanic sequence as a whole is at least garnet grade, their lowest possible metamorphic sub-facies being the chloritoid-almandine sub-facies (Turner and Verhoogen, 1951, p. 461).

Wiseman (1934) noted a change in the refractive index of the hornblende of a suite of metamorphosed basic dykes with progressive metamorphism. He related this change to a change in the chemical composition of the amphibole consequent on a rise in the isotherms during regional metamorphism. However, it is possible to interpret this change in the chemical composition to chemical changes in the environment which were due only indirectly to rising temperatures.

In view of the complexity of the hornblende structure which is capable of so much isomorphous substitution, it is highly unlikely that any systematic temperature-controlled variation will be found, particularly when it has developed in an environment which has suffered numerous periods of varied metasomatism each indicative of chemical change in the environment. The only important change in the nature of the hornblende is the recorded change in colour and form near, and in the gneiss. Here, the brownish, granulose amphibole is quite different from the blue-green prismatic variety in the meta-lavas. Whether this change is due to progressive metamorphism as the gneissic complex is approached, or whether it is due merely to the proximity of a granitization front is not known. Indeed, these rocks, i.e. the gneiss and the adjacent schists, with their peculiar hornblende may be characteristic of a much deeper environment than the adjoining meta-volcanics. This suggests that their present relationship has been brought about by faulting.

Geological History

From our present knowledge it is impossible to set out precisely the sequence of events which have produced this complex. In certain cases the inter-relationship of two rock types is not clear within the area mapped. Such cases will be pointed out.

The oldest rocks in the area are the metasedimentary schists which are overlain by the Phillips River Meta-volcanics. All available evidence suggests that the original superposition is preserved. The original succession was strongly folded and metamorphosed, the fold pattern being modified by the development of a zone of attenuation and shear marginal to the meta-volcanics.

It seems quite certain that all the remaining rock types post-date this period of deformation. The granodiorite is clearly intrusive into the folded volcanics and contains xenoliths which are highly contorted. Within such xenoliths is seen the coarse-grained hypabyssal phase of the meta-lavas, a fact which, with the occurrence of veins of granodiorite in this coarse rock, is definite evidence of the presence of pre-granodiorite coarse amphibolitic intrusives (see Fig. 8).

The gneiss is likewise clearly younger than the adjacent schists, for it occurs as *lit-par-lit* injections parallel to the foliation, forming basic migmatites in the amphibolitic schists. These migmatites also indicate that the main movement on the zone of shear, be it large or small, was pre-gneiss for it produced these amphibolite schists from more massive lavas.

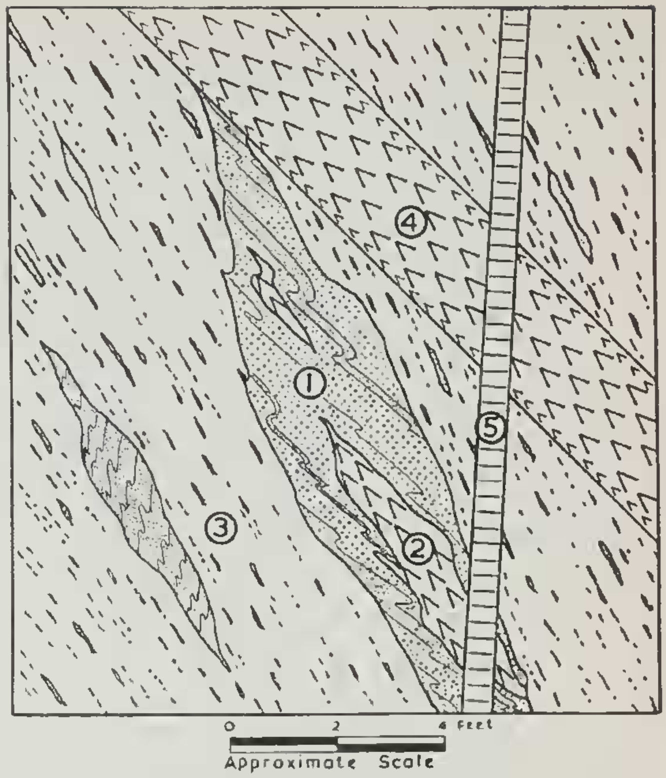
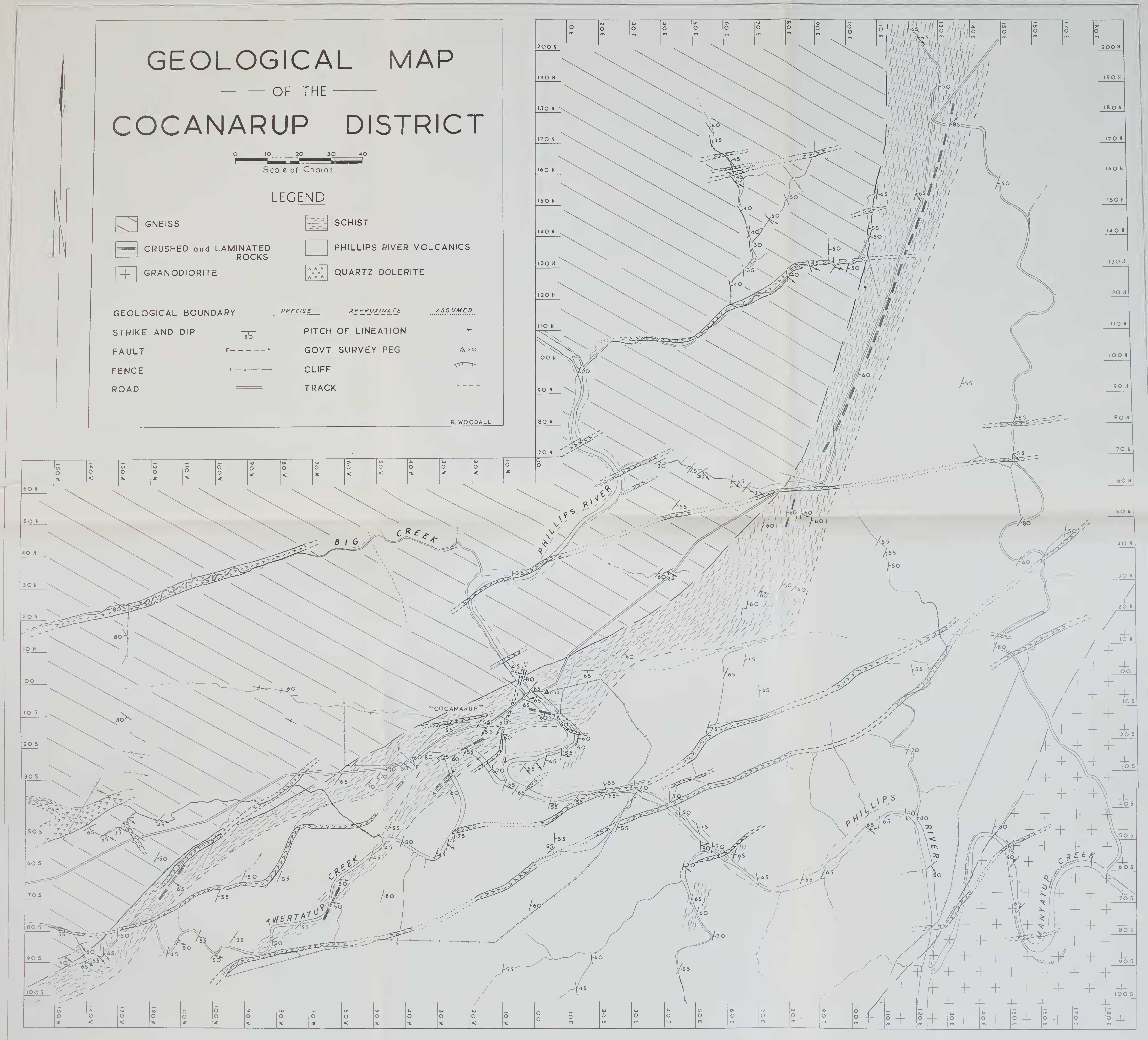


FIG. 8.—A diagrammatic sketch showing the relation between several of the chief rock types of the area, as exposed in a cliff in Manyatup Creek at (80S, 153E). The sketch is drawn in part from photographs. Highly contorted xenoliths of the Phillips River Meta-volcanics (1), contain the coarse hypabyssal phase of the lavas in the form of irregular pods (2). They are not chilled against the host rock. The xenoliths are contained in the flow-banded granodiorite (3) which itself is cut by a dyke of coarse amphibolite (4) exhibiting chilled margins against the country rock. A thin quartz dolerite dyke (5), well jointed and chilled against all of the preceding rock types is also shown.

The relationship between the granodiorite and the gneiss is not so easy to interpret. Theoretically, the gneiss with its granular, completely recrystallized brown-green hornblende, its marginal migmatites and aureole of sillimanite grade metamorphism, is an obvious product of granitization *in situ* and should be a much older and much deeper plutonic mass than the magmatic granodiorite. This latter pluton has well-developed flow structures, xenoliths and contains ragged, blue-green hornblende. The former is equivalent to a deep "autochthonous granite" which precedes the emplacement of a high level "parantochthonous granite" (Read, 1951). However, within the granodiorite and the Phillips River Meta-volcanics are numerous "younger amphibolite dykes", but although many square miles of gneiss have been examined, no evidence of their presence in this rock has been found. Surely a basic dyke swarm such as is indicated by the original mapping of the Geological Survey near Ravensthorpe (Woodward *et al.*, 1909, Geological Map of Ravensthorpe Centre) would have some counterpart in the gneiss if it was in its present position adjacent to the meta-volcanics and within a mile or so of the granodiorite at the time when these rocks suffered this injection of basic magma as there is no great difference in competency between the gneiss and the granodiorite. It is difficult to reach any conclusion other than that the gneiss did not occupy its present position at this time.


GEOLOGICAL MAP
OF THE
COCANARUP DISTRICT
Scale of Chains
0 10 20 30 40
LEGEND
GNEISS
SCHIST
CRUSHED and LAMINATED ROCKS
PHILLIPS RIVER VOLCANICS
GRANODIORITE
QUARTZ DOLERITE
GEOLOGICAL BOUNDARY
PRECISE
APPROXIMATE
ASSUMED
STRIKE AND DIP
PITCH OF LINEATION
FAULT
GOVT. SURVEY PEG
FENCE
CLIFF
ROAD
TRACK
R. WOODALL
BIG CREEK
PHILLIPS RIVER
"COCANARUP"
TWERTATUP CREEK
MANYATUP CREEK
PHILLIPS RIVER